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DYNAMIC CERTIFICATION AND ASSESSMENT OF THE BUILDINGS LIFE CYCLE UNDER REGULAR EXPLOSIVE IMPACTS

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Abstract. Today in Ukraine, there is no single legalized, generally accepted methodology (at the level of a Ukrainian building standard) for dynamic certification of buildings and structures. A unified approach is proposed as such a technique. It includes four components: visual inspection of buildings; experimental studies of the dynamic response of buildings or structures to explosive effects; mathematical modeling of the stress-strain state of the object under study; synthesis of the results of visual inspection; experimental studies and numerical simulation in order to generalize them systematically. As an approbation, the deterioration of the resource of reinforced concrete structures of residential buildings under the conditions of constant mass industrial explosions with a capacity of 500 to 700 tons in the quarry of Southern GZK (Mining and Processing Plant) in the city of Kryvyi Rih, Ukraine, has been studied. Based on the processing of numerous experimental data and the results of mathematical modeling, a probabilistic model for predicting the deterioration of the technical condition of reinforced concrete structures of the Center for Children and Youth Creativity "Mriya" has been obtained. Calculations of the risks of destruction of the building's load-bearing elements for its vulnerable areas made it possible to clarify its service life. It decreased by ~ 30 years compared to the standard in 2012.

Keywords: shock waves, experiment, risk, dynamic certification, life cycle of buildings and structures.

INTRODUCTION

Due to the insufficiently developed network of roads and land transport in the USSR and for the economic feasibility reasons, the residential neighborhoods were usually built near industrial zones. That ensured minimal time expenditures for workers transportation to the enterprises in those zones. At the same time, the nature of the works performed in industrial zones and their impact on the housing stock were minimally taken into account during housing development design and construction. The housing stock buildings in the city of Kryvyi Rih (Dnipropetrovsk region, Ukraine) can be mentioned as a typical example of man-made influences during blasting works in open iron ore quarries. The buildings and structures dynamic certification is the primary stage of works to ensure the necessary and economically feasible level of construction projects dynamic stability in conditions of industrial explosions, moral wear and physical tearing. Two main goals of the buildings and structures dynamic certification include:

1) comparative assessment of the actual seismic resistance of buildings with the specified territory seismicity (the determination of the buildings seismic resistance deficiency);

2) identification of the most dangerous projects that require priority strengthening, repurposing or demolition of the buildings.

The issues of the buildings dynamic certification, physical and dynamic wear impact and earthquake-resistant construction economic feasibility were given a serious attention at the state level in the relevant resolutions and other documents of the Cabinet of Ministers of Ukraine [1, 2], as well as considered in the numerous works of Ukrainian and foreign researchers including S.V. Medvedev, V.I. Keilis-Borok, I.E. Itskov, Y.M. Eisenberg, M.A. Cornell, K. Oliveira, I. Idriss and others [3–10]. The known scientists A. Alonso-Rodriguez, M. Barla, H. Burton, N. Casagli, F. Catani, C. Del Ventisette, W. Frodella, G. Gigli, G. Kampas, G. Lollino, G. Luzi, M. Martinelli, R. Piccioni, J. Stewart, Y. Wang and others should be mentioned among modern foreign researchers in the field of structures dynamic analysis [11–21].

The existing certification methods can be conditionally divided into the following three groups: expert assessment methods, analytical calculation methods, and technical diagnostics methods.

Their comparative analysis shows that, in addition to advantages, the existing certification methods have several disadvantages [22, 23]. When using the expert assessment method, the statistical consistency degree of expert assessments and their confidence intervals remain uncertain. Although this method, in an opinion of several researchers [2, 22, 23], is the cheapest and the most common when the actual seismic resistance of buildings is continuously assessed. At the same time, according to other researchers [24], it gives a rather high error.

The analytical calculation methods related with DBN [25, 26] reflect the inherent contradictions in the normative calculation procedures (conditional design loads or linear elastic models use). Their advantages include taking into account the actual physical and mechanical characteristics of the structures material and the possibility of considering the building structures physical tearing. However, they are labor-intensive and require a lot of time.

The technical diagnostics methods allow to detect and localize an anomaly of the building dynamic structure, but at the same time they cannot establish its cause and reveal by means of the structures opening the respective defects of structural elements and their connection nodes. Usually, the analysis of the building dynamic structure is carried out at the microdynamic level of impact, at which the structures and their connections clearly operate in the elastic stage. This does not allow to take into account the influence of structural and physical nonlinearity and stiffness parameters degradation on the assessment of the building seismic resistance.

Due to the described above advantages and disadvantages, specific for each of the three approaches, the methodological problems of the dynamic certification can be reduced to two main problems [24].

The first problem is the correct definition of the criterion for assessing the inspected building dynamic stability reserve including:

1) the expert assessment reflecting the degree of project compliance with structural requirements [25];

2) the computational and analytical assessment of seismic resistance corresponding to conditional seismic loads [25];

3) the results of the building technical diagnostics [27].

The second problem is the determination of the necessary level of influence, at which the building dynamic structure including the microdynamic level at the elastic stage of the structures operation or the load level corresponding to the building structures operation beyond the elastic limit should be investigated.

Thus, it can be concluded that in Ukraine today there is no unified dynamic certification method legalized at the level of DBN [26, 28, 29] or standard. In view of this, the methods improvement for the buildings inspection to assess their actual seismic resistance and determine the residual resource with an allowance for the structures physical tearing, is an urgent task.

The paper proposes to synthesize the methods into a unified VEMS method consisting of four parts: **v**isual inspection of buildings – the first part; experimental studies of the dynamic response of buildings or structures to explosive actions – the second part; mathematical modeling of the stress-strain state of the project under study – the third part; **s**ynthesis of the results of visual inspection, experimental studies and numerical modeling with an aim of their systematic generalization – the fourth part.

Visual examination. Today, the man-made impact of industrial explosions on the existing housing stock and socio-cultural assets of Kryvyi Rih has significantly increased. This is primarily due to the expansion of the iron ore quarries industrial zone. For example, the open pit of the PivdGZK (Southern Mining and Processing Plant) for the iron ore extraction in the city of Kryvyi Rih was founded in 1952 and reached a depth of about 250 m. At ground level, the development of minerals in the quarry is carried out on the area outlined by an oval with the major and minor axes of 4 km and 3 km, respectively (sanitary and protective zone during explosions is 700 m). The general appearance of the quarry of the Kryvyi Rih Southern Mining and Processing Plant is presented in Fig. 1.

Fig. 1. General view of the PivdGZK quarry with the adjacent infrastructure of the Inhulets district of the Kryvyi Rih city

The boundary of the housing area of the Inhulets district of the city located to the east and southeast of the quarry passes at an 800–900 m distance from its eastern edge. Thus, during blasting operations at the quarry upper horizons, the sanitary protection zone directly approaches to the residential development territory. The seismic impacts on buildings located in the sanitary protection zone are periodic in nature. Until recently, explosions at the PivdGZK were carried out once every 2 weeks. At the same time, the maximum mass of explosives for carrying out explosions in the PivdGZK quarry ranged from 490 to 652 tons during the observations period in 2008–2012.

For the observations during the blasting works in the quarry the following objects are selected: secondary school No. 40, the Center for Children and Youth Creativity (the Center), the Church of the Nativity of the Theotokos, and three one-storey buildings measuring $\approx 7 \times 8$ m. The listed structures do not cover the comprehensive spectrum of buildings according to their structural design, but they fully correspond to their socio-cultural purpose. The School, the Center and the Church of the Nativity of the Theotokos are, in addition, the buildings of mass concentration of people and must satisfy the increased safety requirements during their operation. The assessment of their current state under the seismic effects from explosions, predictive assessment of their durability (resource) and, therefore, of the people safety include the stated task in the category of actual problems.

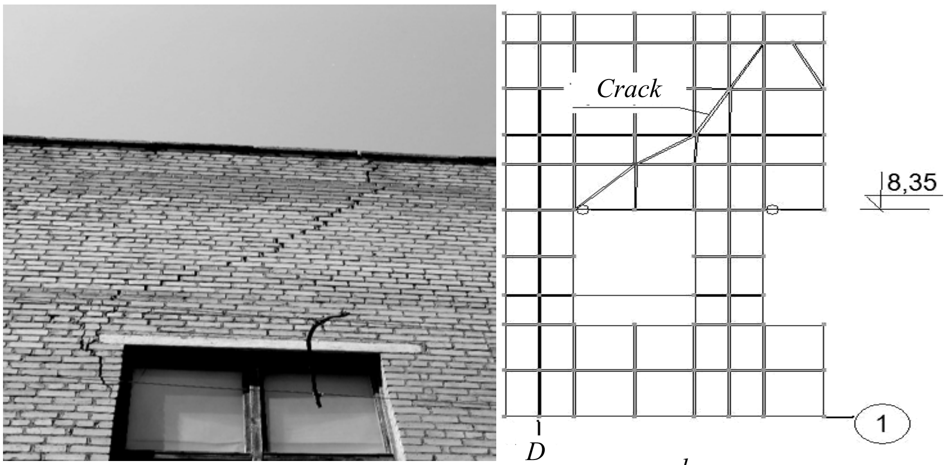
In the photographs (Fig. 2) the fragments of the Church of the Nativity of the Theotokos at 14, Obrucheva St. in Kryvyi Rih, located between two iron ore quarries are shown.

Fig. 2. Instances of buildings damages due to industrial explosions in Kryvyi Rih (photographs by Iurii Kaliukh)

Due to its proximity to the quarries, the building is exposed to a double "dose" of man-made seismic actions from industrial explosions in two quarries at once, as can be seen from the recently installed and already cracked glass at the entrance (Fig. 2, *a*) and vertical cracks in the wall (Fig. 2, *b*). In Fig. 2, *c* the church priest presents vertical cracks on his house located on the territory of this church. In Fig. 2, *d* the damage to the load-bearing walls of the secondary school No. 40 building, which is located next to the iron ore quarry, is shown. By the cracks nature, it can be assumed that the school is in an emergency state resulting from the regular and constant man-made tremors posing a serious threat, which to the students at the school are exposed every day during classes.

Many of the observed buildings have a long-term service life. The design and executive documentation of some buildings has now been lost. Therefore, all three methods (visual, experimental and theoretical) for the assessment of the buildings and their load-bearing elements technical condition should be used. The Center of Creativity building in the Kryvyi Rih city could be considered as an example. The choice of this building for the detailed experimental and theoretical research, as well as for the residual resource assessment was also reasoned by the partial availability of design materials. The building design was developed in 1960. The Center of Creativity was built in the 70s during the period of intensive extraction of iron ore in the quarry, therefore the building has been subjected to explosive influences, starting from the construction stage.

In Fig. 3 the area of the load-bearing wall along the axis 1 with an oblique crack starting from the window opening corner at the second floor, and its modeling via the building computer model using the finite element method are shown. Cracks with openings smaller than the above one were not modeled.



a *b*

Fig. 3. Photo recorded view of the Center bIuilding wall along the axis 1 and an arrow indicating the crack in the damaged area (*a*) and its representation in the computer model N 2 (*b*)

Experimental studies. It is possible to consider in more detail the features of dynamic diagnostics of building structures (floor slabs) with small-amplitude vibrations (from fractions of a mm to several mm) using high-sensitivity sensors that can record and single out the buildings vibrations arising due to the background dynamic loads from industrial explosions. In the 2008–2012 period the Center building and soil dynamic examinations were carried out according to the developed methodology, which envisaged the selection and composition of vibration measuring equipment and the development of the vibration sensors arrangement schemes and methods for recording, storing and processing the received vibration signals. In Fig. 4 the scheme for recording the shock waves propagation is shown.

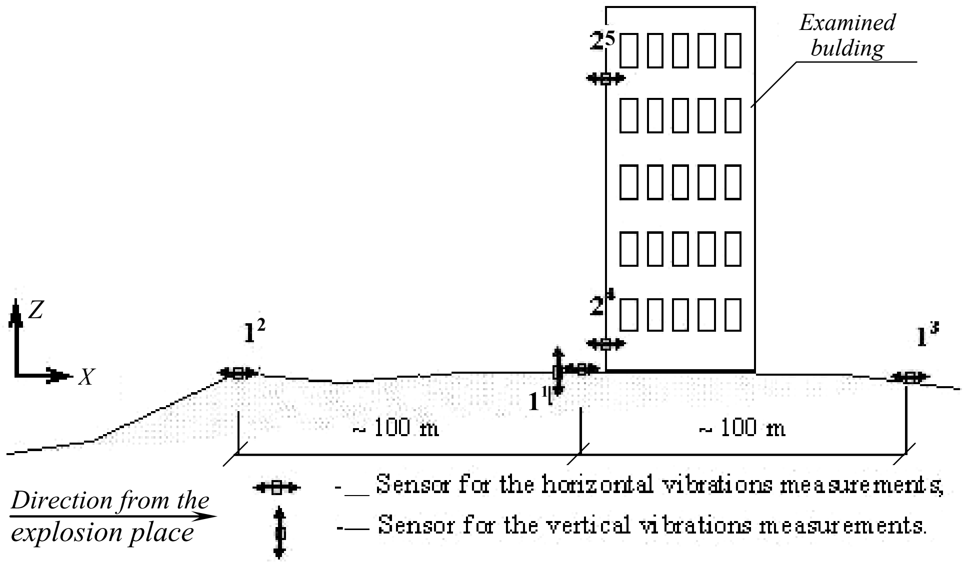


Fig. 4. Sensors arrangement according to the diagsrams 1 and 2

A typical spectrum of the time signal of vibration acceleration and the amplitude spectrum of the examined project reinforced concrete floors vibrations are presented in Fig. 5.

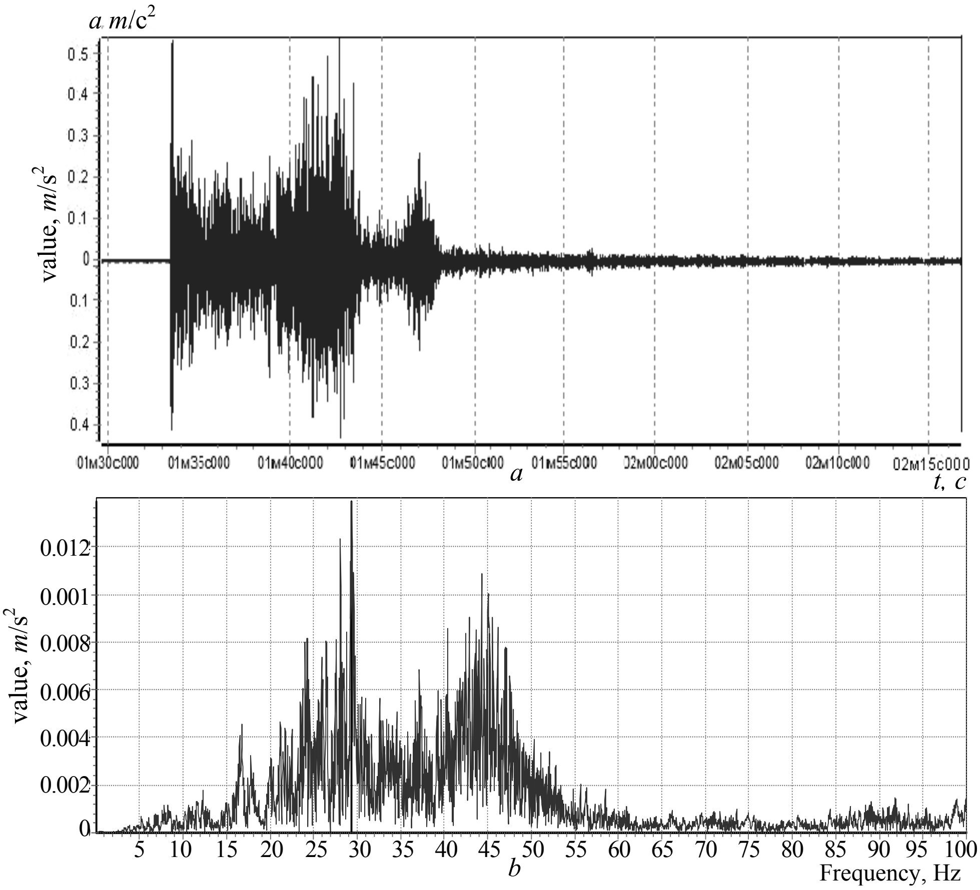


Fig. 5. The time-dependent signal of the radial component of the soil horizontal acceleration near the Center for Children's Creativity building (*a*) and its amplitude spectrum (*b*) during an explosion with a power of 650 tons, 2012

Based on the obtained experimental data concerning the actual levels of acceleration and vibration velocity of the soil and Center building structures the following conclusions can be drawn:

1. The values of the soil vibration accelerations at the buildings bases recorded during explosions are in the range [0.0238 m/s^2 to 0.643 m/s^2].

2. The values of the soil vibration velocity at the buildings bases recorded during explosions are in the range of 0.0004–0.015 m/s [31], which corresponds to 1–4 points on the S.V. Medvedev's seismic intensity scale [30].

3. The spectra analysis of the soil accelerations during explosions allows to find out that the predominant frequencies are in the range of 1–54 Hz. This confirms the possibility of building structures (floor and walls) vibrations in a mode close to resonance. In addition, according to recommendations [31], for the exclusion of the building foundations settlements during explosions, the soil acceleration should be limited to 0.15 m/s^2.

Mathematical modeling. For the further research and examination of the Center building condition, its computer model was developed based on the finite element method (FEM) with the use of the LIRA-9.6 software package [32]. The LIRA software package is a multifunctional software package for calculation, research and design of structures for various purposes, which has more than 40 years of history of creation, development and use in the scientific research and practice of structures design.

The FEM is the theoretical basis of the LIRA software package. The FEM implemented version uses the principle of possible motions:

$$a(u,v) = (f,v)\,, \tag{1}$$

where *u* is the desired exact solution; *v* is any possible displacement; $a(u,v)$ and (f,v) are the possible actions of external and internal forces (1).

The area occupied by the structure is divided into finite elements Ω_r; the nodes and their degree of freedom L_i (nodes displacements and rotation angles) are assigned. The degrees of freedom have corresponding them basic (coordinate or approximating) functions μ_i that differ from zero only at the elements corresponding nodes and correspond to the following equality:

$$L_j\mu_i = \begin{cases} 1, & i = j; \\ 0, & i \neq j. \end{cases} \tag{2}$$

The approximate solution U_h must satisfy the main kinematic conditions and is calculated in the form of a linear combination of basic functions

$$U_h = \sum_{i=1}^{N} u_i\mu_i\,, \tag{3}$$

where u_i are the numbers; N is the number of degrees of freedom.

Substituting U_h instead of *u* and μ_i ($i = 1..N$) instead of *v* in (2) allows to obtain a system of FEM equations shown in the elements of the block-diagram in Fig. 6.

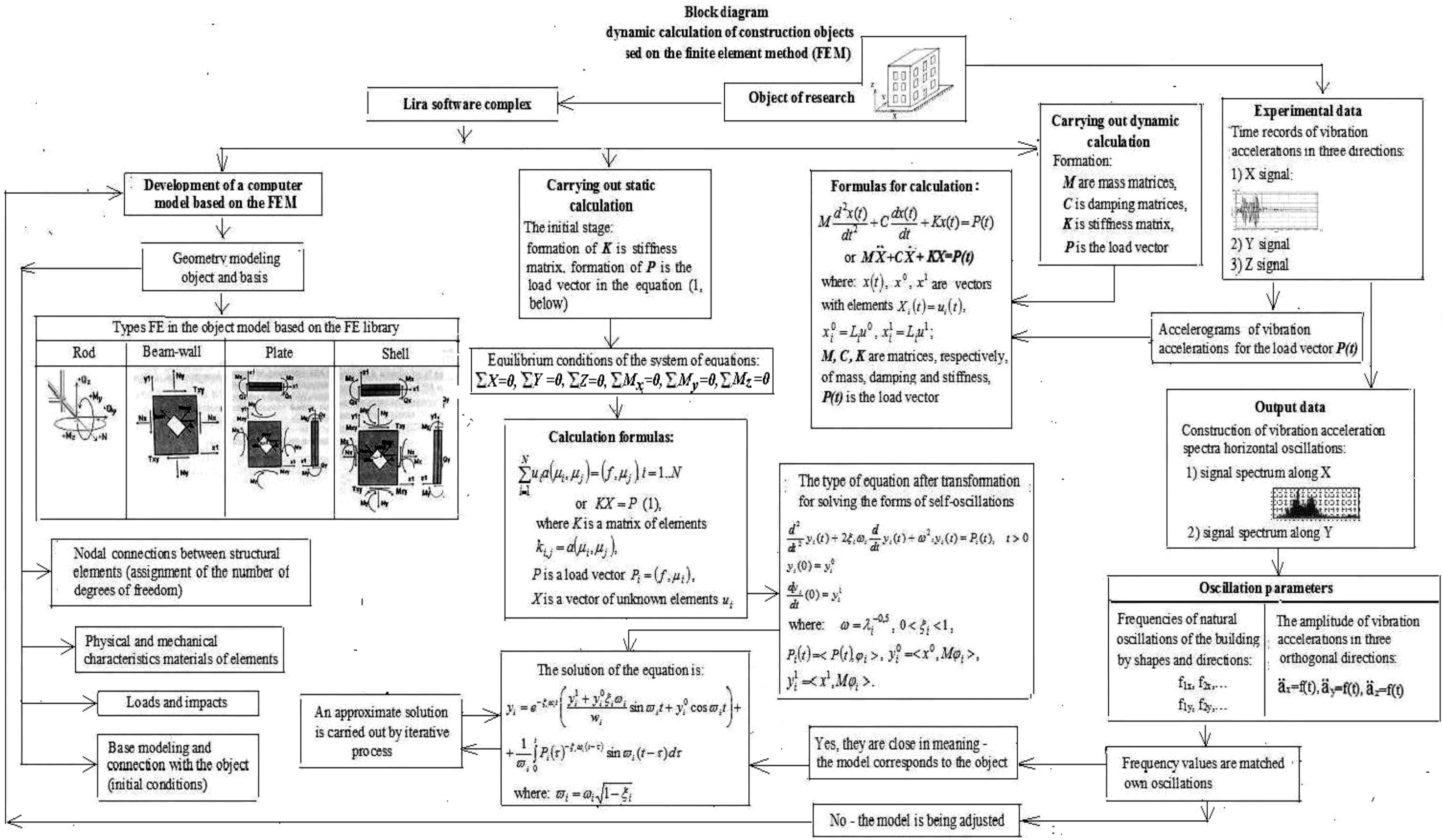


Fig. 6. Block-diagram of construction projects dynamic analysis based on the finite element method (FEM)*c*

Thus, the FEM use reduces the problem to a system of linear algebraic equations. An important advantage of the described method is that the ***K*** matrix and the ***P*** vector are obtained by summing the corresponding elements of the stiffness matrices and load vectors constructed for the individual finite elements. The Finite Element Library (FEL) contains elements to model the operation of various types of structures including the rod elements; the quadrangular and triangular elements of a planar problem such as slabs or shells; the spatial problem elements, for instance, tetrahedron, parallelepiped or trihedral prism. In addition, there are various special elements in the FEL that model the connection of finite stiffness, elastic compliance between nodes, or elements specified by the numerical stiffness matrix. All finite elements in the FEL are theoretically justified and the energy and displacement error assessments are obtained for them.

In the dynamic analysis, the principle of possible FEM displacements is changed in comparison with the static calculation according to formula (1) and takes the following form:

$$b(u,v)+c(u,v)+a(u,v)=(f(t),v)\,,\ t>0\,, \tag{4}$$

where u is the desired exact solution; v is any possible displacement; $b(u,v)$ and $c(u,v)$ are the possible actions of inertial and damping forces, $a(u,v)$ and $(f(t),v)$ are the possible actions of external and internal forces. The problem of dynamic analysis is formulated in the form of a variational equality with partial derivatives:

$$b\left(\frac{\partial^2 u}{\partial t^2},v\right)+C\left(\frac{\partial u}{\partial t},v\right)+a(u,v)=(f(t),v),\quad t>0\,;$$

$$u(0)=u^0\,;\ \frac{\partial u}{\partial t}(0)=u^1\,, \tag{5}$$

where $u_i=u(t)$ is the exact solution; u^0 and u^1 are the initial values of displacement and velocity; other values are the same as in the static problem.

The method of the dynamic problem solution implemented in the LIRA software envisages combining the FEM with the decomposition according to the natural vibrations shapes. The solution (5) is searched in the following form:

$$U_h=\sum_{i=1}^{N}u_i(t)\mu_i\,, \tag{6}$$

where $u_i(t)$ are the scalar functions; μ_i are the basic functions of the corresponding static problem.

Substituting, by analogy, U_h instead of u and μ_j ($j=1..N$) instead of v in (5), a system of ordinary differential equations given for the block-diagram elements for dynamic analysis in Fig. 6 is obtained. The equation written in a matrix form is also given there. In the above equation from the block-diagram, the mass matrix M is determined by the elements $m_{i,j}=b(\mu_i,\mu_j)$, and the damping matrix C — by $c_{i,j}=c(\mu_i,\mu_j)$, respectively. The stiffness matrix K is determined by the elements $k_{i,j}=a(\mu_i,\mu_j)$ and the loading vector $P(t)$ is determined by the elements $P_i=(f(t),\mu_i)$ by analogy with a static problem.

$$M\frac{d^2x(t)}{dt^2}+C\frac{dx(t)}{dt}+Kx(t)=P(t), \tag{7}$$

where $x(t)$, x^0, x^1 are the vectors with the elements $X_i(t)=u_i(t)$, $x_i^0=L_iu^0$, $x_i^1=L_iu^1$.

This method is known as semi-discrete approximation. Its error (the difference between U and U_h) in terms of the potential and kinetic energy is assessed in both compatible and incompatible cases by a value proportional to h^τ.

System (7) is calculated by the method of decomposition by the natural vibrations shapes. Let λ_i, φ_i be the eigenvalue problem solution; $<M\varphi_i,\varphi_i>=1$, where the symbol $<,>$ denotes the scalar product:

$$K\varphi=\lambda M\varphi. \tag{8}$$

The eigenvalue problem (8) is calculated by the subspace iteration method. Considering that in (7) $x(t)=\sum_{i=0}^{N}y_i(t)\varphi_i$, the orthogonality of the function φ_i will ensure (under certain assumptions about the matrix *C*) the system (7) disintegration into independent equations with respect to $y_i(t)$, which are presented in the block-diagram for the natural vibrations shapes solution (6).

The equation solution with respect to $y_i(t)$ is as follows:

$$y_i=e^{-\xi_i\omega_i t}\left(\frac{y_i^1+y_i^0\xi_i\omega_i}{w_i}\sin\varpi_i t+y_i^0\cos\varpi_i t\right)+\frac{1}{\varpi_i}\int_0^t P_i(\tau)^{-\xi_i\omega_i(t-\tau)}\sin\varpi_i(t-\tau)d\tau,$$

where $\varpi_i=\omega_i\sqrt{1-\xi_i}$. The vectors of the inertial forces $S_i(t)$ are calculated by the formula $S_i(t)=\omega_i^2y_i^{(t)}M\varphi$. The values $S_{i,0}=_t^{\max}\{|\,\omega_i^2y_i(t)\,|\}$ are used for calculations. Their values are selected depending on the loads type including wind, seismic, impulse, impact, or harmonic loads.

The time-dependent dynamics generally involves the four loads specifying as follows:

The first load is a static load to the structure. For example, dead load of the structure or self-weight with technological load etc. (it is not mandatory for specifying and may be absent). The static influences are specified in the form of concentrated forces and moments both at the scheme nodes (nodal loads) in the directions of the global and local coordinate systems axes, and at the elements (local loads) in the directions of the local or global coordinate system.

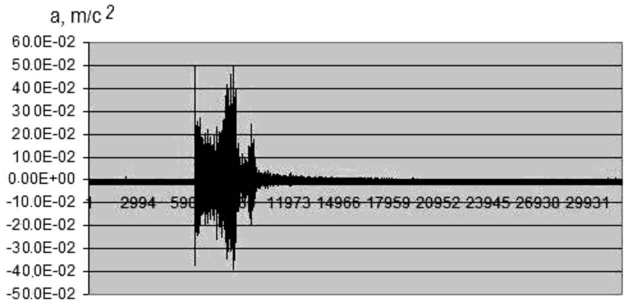
The second load characterizes the inertial characteristics of the structure (mass distribution). It can be collected from the first load, from the elements density, by concentrated masses specifying in the second load, or by the listed options combination.

The third load establishes the active dynamic load for the structure. In the LIRA-9.6 software package [32], four types of dynamic loads are implemented: a broken line with arbitrary segments (the quantity of points pairs and the "time – value" points pairs themselves are specified); a sinusoidal load specified as $A\sin(\omega t+\varphi)$; an accelerogram; a broken line with uniform segments (the points quantity, start time, sampling step, scaling factor and broken line value are specified). The dynamic effects are specified as nodal loads acting along the axes of the global or local coordinate systems. The weight of the structure mass is specified as the dead load of structures, equipment etc., while the use of both local and nodal loads is allowed.

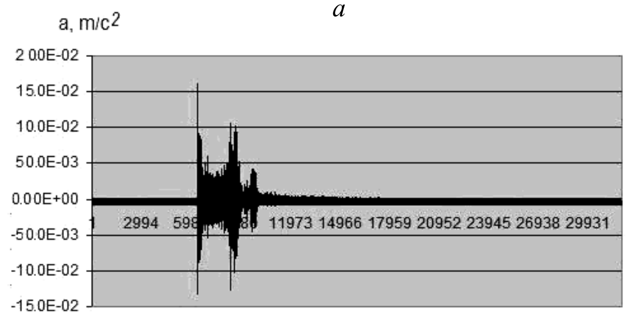
In the fourth load, the structure damping characteristics are specified (they are not mandatory for specifying and may be absent). The load direction is not important, because all values are taken according to their absolute values and in the process of integration the damping forces will be directly proportional to the velocities.

The boundary conditions in the design scheme can be specified directly for the node, as well as modeled using finite stiffness connections. The latter is especially effective if it is necessary to define responses in overlapping connections. After specifying two to four loads in the sequence indicated above, for successful execution of the calculation it is necessary to specify the parameters for the displacements equations integration and specify just which calculation results are required by the user: only displacements, displacements and forces, or displacements, forces and calculated combinations of forces.

Loads and actions are set according to the DBN [33] and seismic effects are taken into account based on the DBN [25]. It should be noted that the actual soil accelerograms of radial and tangential direction affecting the building at angles of 45° and 135°, respectively, are accepted as the external seismic effects on the building under consideration. The accelerograms were recorded near the building on 05/16/2012 during a massive explosion of 652 tons in the PivdGZK quarry. Graphs of digitized accelerograms of the radial *R* and tangential *T* directions are plotted in Fig. 7.



a



b

Fig. 7. Calculated accelerograms of radial *R* (*a*) and tangential *T* (*b*) components of the seismic effect on the Center building

The accelerograms feature the following main parameters: 4 ms discretization step, 245 s total impact duration, 17 s explosion duration, 0.5 m/s maximum accelerogram value for the seismic impact radial component R, and 0.15 m/s maximum accelerogram value for the seismic impact tangential component T. Two design schemes of the building are created for conducting the theoretical studies: scheme 1, in which there is no damage, and scheme 2 with the main damages in the load-bearing walls of the Center building (Fig. 3, *b*):

- the design scheme 1 reflects the original building condition at the time of its commissioning (≈1969–1971);
- the design scheme 2 reflects the building condition at the time of the inspection (May 2013).

The digital values of the stress-strain state dynamic parameters of the Center building computer model are the main criteria for checking the model correctness (comparison was made with the results of experimental and visual inspections of the Center building). The directions of the seismic effects on the building during explosions are shown in Fig. 8, where the Center building computer model is presented.

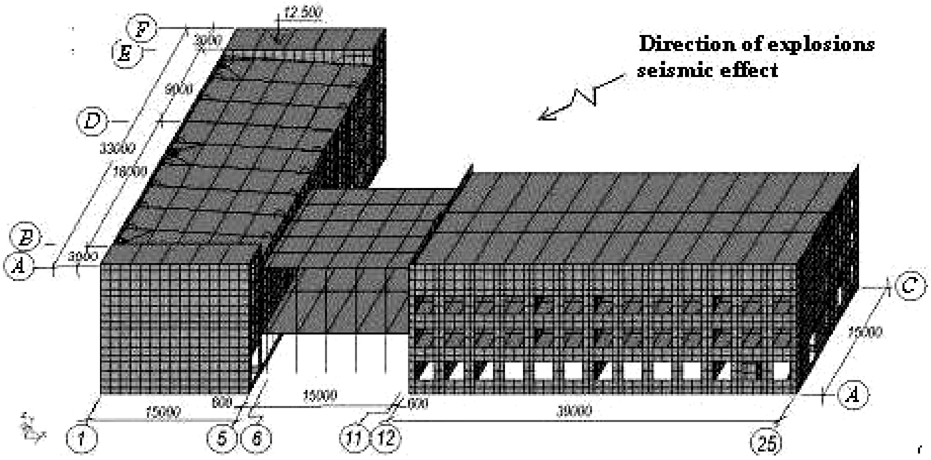


Fig. 8. The general view of the computer model of the Center for Children and Youth Creativity "Mriya" building in the Kryvyi Rih city

The design scheme 1 is created based on the following types of finite elements: rod elements of type 10 (six degrees of freedom at the node) and plate elements of types 41, 42 and 44 (six degrees of freedom at the node). The building stabilization is done at the base level. For nodes of plate elements adjacent to the base the angular displacements are allowed. The column nodes at the level of the base are constrained. The calculations at that stage are performed in a linear version.

In Fig. 3, *b* the section of the load-bearing wall along axis 1 with an oblique crack passing from the window opening corner at the second floor and its simulation in the building computer model are shown. Cracks with openings smaller than the shown one (Fig. 3, *b*) are not modeled. The crack is modeled in the LIRA-9.6 software package [32] with the use of the finite element method for dividing the nodes and elements of the building computer model connected along the crack line and combining these nodes displacements in the direction of existing connections in the building computer model.

The building dynamic parameters in the design scheme 2 are accepted for the further analysis if they are close to the experimental data, or if necessary, they are corrected by iterative calculations to refine the design scheme. Also, the dynamic parameters of the computer model are the main criteria for confirmation its similarity to the real building. When the dynamic analysis of each of the mentioned design schemes (1 and 2) was performed, the number of specified vibrations shapes corresponded to 10.

Table shows the design values of the natural vibrations frequencies for the design scheme 2 of the building with damage, as well as experimentally recorded values.

For that condition, the experimental values of the natural vibrations frequencies of the Center of Creativity building for the first main shapes of vibrations in the directions of the numerical and letter axes were obtained during experimental vibrodynamic surveys conducted on 16.05.2012.

Table. Dynamic characteristics of the Center building computer model 2

Numbering of vibration shapes	**Frequency of vibrations, Hz (design)**	**Frequency of vibrations, Hz (experimental)**	**Relative error, %**	**Vibration period, s**	**Sum of modal masses during seismicity, %**	
					for X	for Y
1	4.561	4,25	7,3	0.219	55.570	12.725
2	4.693	-“-		0.213	59.979	65.489
3	5.161	-“-		0.194	59.997	65.607
4	5.355	-“-		0.187	60.006	65.609
5	5.669	-“-		0.176	60.046	65.635
6	5.712	-“-		0.175	60.046	65.639
7	6.219	6,7	7,2	0.161	75.127	72.458
8	6.246	-“-		0.160	76.368	73.025
9	6.678	-“-		0.150	76.927	74.082
10	6.751	-“-		0.148	76.934	74.092

Note. The vibration shapes determining the parameters of the building stress-strain state are indicated by the filling.

During the vibrodynamic surveys of the Center building, based on the experimental data an amplitude spectrum of vibration accelerations was obtained (Fig. 5), according to which the experimental values of natural vibrations frequencies f_i (and periods T_i) of the building by the shapes were obtained:

— for X direction: $f_1 = 4.50\,\text{Hz}\ (T_1 = 0.235\,\text{s})$, $f_2 = 6.70\ \text{Hz}\ (T_1 = 0.149\,\text{s})$;

— for Y direction: $f_1 = 4.50\,\text{Hz}\ (T_1 = 0.222\,\text{s})$, $f_2 = 5.40\ \text{Hz}\ (T_2 = 0.185\,\text{s})$.

In Table for the building computer model 2 the values of natural vibrations frequencies and periods according to shapes 1, 2, 7 are close to their experimental values (a relative error does not exceed 7.3%). Thus, the Center building computer model 2 with the crack simulation in the upper part of the building load-bearing wall along the axis 1 was verified as a starting point for mathematical modeling of the stress-strain state of the Center building.

Along with the dynamic parameters assessment, the developed computer model 2 performed an assessment of the building stress-strain state under dynamic influences. The maximum displacements reaching 0.0503 m during the dynamic explosion influences on the building in the *X* direction were obtained for the wall along the axis 1 in the area in the B–I axes (Fig. 7). The deformed state of the building wall along the axis 1 in the *X* direction was graphically displayed in 3D in Fig. 9.

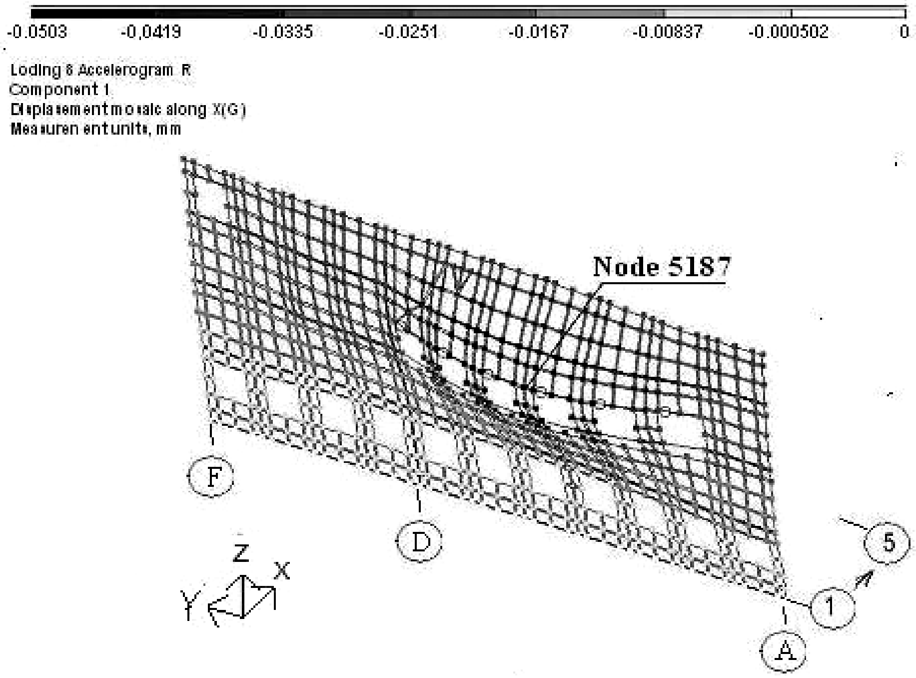


Fig. 9. The deformed state of the building wall along the axis 1 under seismic effects in the *X* direction

The auditorium space of the Center for Creativity on the second floor of the building is limited by the presented area of the load-bearing brick wall along the axis 1 with the largest deformations under seismic effects, which is the most dangerous for spectators. The reinforced concrete covering beams at 10.85 elevation and the upper belt of the transverse frame along the I axis at 11.80 elevation that bear the covering elements, are the most responsible structural elements of the building roof, therefore they determine its durability (resource). The destruction risks calculation was performed for those elements to determine the reduction of those elements resource under the seismic loads influence. The calculation results are given in the paper [34].

System analysis. The final diagram of the load-bearing capacity changes for a separate load-bearing element and the entire Center building is presented in Fig. 10 based on the synthesis of visual inspection, experimental studies and mathematical modeling materials.

Each section of the diagram of the building bearing capacity changes is constructed for a time interval of about 30 years and covers the entire period of the design building operation of ≈100 years. The diagram represents four categories of the building technical condition defined according to [34]. Graph 2 of the building bearing capacity changes during the operation time T is a smooth curve described by the theoretical dependence $P = P_0 - \Delta P(T, T^2)$. The points, where the vertical line drawn from the middle of the interval of each section of the building bearing capacity changes diagram and graph 2 intersect, determine the values and positions of the diagram sections for the corresponding categories of the building technical condition.

That dependence 2 does not describe existing defects and effects. But if they are taken into account, it becomes possible to assess the building technical condition and, according to the given diagram, to assess its bearing capacity.

At any moment the bearing capacity of a separate load-bearing element of the building under the external forces actions (for instance, seismic effects) should a priori be greater comparing to the building itself and its serviceability should be longer. Graph 1 in Fig. 10 corresponds to that conclusion. Accordingly, graphs 3 and 4 compared to graph 2 a priori demonstrate the decrease of the bearing capacity of the building and of its service life when there are seismic effects (graph 3) or they are combined with a damage (graph 4).

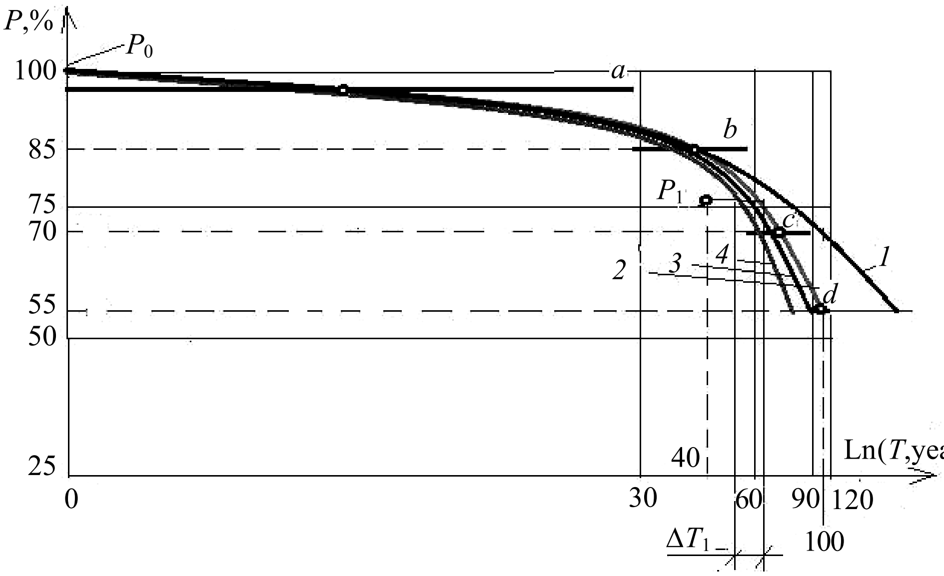


Fig. 10. Comparative graph of the load-bearing capacity changes depending on the period of operation for the load-bearing structural element of the Center building and for the entire building. Segments of straight lines *a*, *b*, *c*, *d* are the elements of the diagram of the entire building load-bearing capacity changes for four categories of technical condition during the entire period of the building operation: building in *a* — normal condition, *b* — building in a satisfactory condition, *c* — building unsuitable for normal operation , *d* — building in an emergency condition; *1* — graph of the load-bearing capacity changes in a separate load-bearing structural element of the building under seismic effects, *2* — graph of the load-bearing capacity changes in the building as a whole without seismic effects, *3* — graph of the load-bearing capacity changes in the building without damage during seismic effects, *4* — graph of the load-bearing capacity changes in the building with damages during seismic effects; point P_1 characterizes the technical condition of the Center building at the time of research (2012) after 40 years of its operation

At the initial stage of the building or the load-bearing element operation (within 30 years) the load-bearing capacity changes over time are insignificant, even under the seismic loads effects and damages occurrence. The reduction of the building service life in this case will be $\Delta T \approx 0$ (identity of graphs 1, 2 and 4 at this area).

As the period of building operation increases, the effect of seismic loads from industrial explosions and its combination with the building structures damages cause the development of detected defects and, accordingly, the accelerated decrease of the building bearing capacity. According to the DSTU, the building emergency condition is determined by the reduction of the building bearing capacity to a value of 55% of the initial value (100%).

The building technical condition determination is carried out based on the visual and instrumental inspections of load-bearing and envelope structures. Clarification of the building bearing capacity value is carried out using the computer models analysis with taking into account the results of the above-mentioned inspections.

The building inspections for its technical condition determining and appropriate calculations performing for the bearing capacity assessment allow to determine the service life reduction ΔT at the time of the inspections according to graphs 2 and 4. In Fig. 10 the value of the building bearing capacity P_1 for the operation period of 40 years is shown. During that period of the building operation the value ΔT_1 undergoes lowering.

For the bearing capacity emergency value of P=55%, the design building service life will be reduced to the maximum value $\Delta T_{\max}$. In this case, the calculated building service life compared to the design $T_{пр}$ =100 years will be reduced to the $T=T_{пр}-\Delta T_{\max}$ value.

To prevent a significant reduction of the building service life in the presence of damages and seismic effects, it is necessary to increase the frequency of visual and instrumental inspections after 40 years of building operation. The building bearing capacity clarification based on the building computer model relevant calculations should preferably be carried out taking into account the new inspection data for the period of building operation of 60 and 70 years.

The reliability and in-depth analysis of the obtained data for the likely continuation of experimental studies of the Center building must be ensured by repeating, as a prerequisite, the schemes, quantitative composition, as well as the types of vibration transducers and their arrangement on the building structures, which were used during the primary study. If necessary, the layouts of vibration transducers arrangement can be supplemented based on the results of visual inspections.

As a result, it can be seen from Fig. 10 [35; 36] that the design age of the Center building differs from the actual one by ~ 30 years. Thus, for a comprehensive assessment of the life resource of the Center of Creativity building, it is necessary to take into account the technical condition of all its elements and the results of all types of surveys, including the instrumental and visual inspections, as well as the results of mathematical modeling.

The defects revealed by the visual inspection in combination with calculated and experimental data allow to characterize the general technical condition of the Center building as unsuitable for normal operation already in the nearest future. With the growth of internal defects in the load bearing reinforced concrete structures, the risk of their destruction will increase, which will accelerate the building aging and its resource significant reduction (increase of ΔT_1).

CONCLUSIONS

1. Based on research and experimental data obtained in 2005–2012 the intensity of the dynamic effects caused by explosions at the PivdGZK quarry on the

housing stock of the city of Kryvyi Rih is assessed to be within 2–3 (4) points range (the velocity of soil vibrations near buildings varies within 0.002–0.004 m/s). At the same time, the maximum mass of explosives for explosions in the PivdGZK quarry during the 2008–2012 observation period is from 490 to 652 tons.

2. The use of only technical means (use of decelerators during explosions) for the reduction of the level of seismic effects on buildings and soil during explosions weighing 500–650 tons in the PivdGZK quarry does not allow to significantly reduce their intensity.

3. Based on a systematic combination of numerous experimental data and mathematical modeling results, the technical condition deterioration forecast for the Center building reinforced concrete structures in the conditions of permanent explosive impacts from the PivdGZK quarry is obtained. The risks of the Center building load-bearing elements destruction are calculated for all vulnerable zones, which allows to predict and assess the service life resource that decreased compared to the normative one by ~ 30 years.

4. The rate of the Center building life resource decline is determined. The defects detected during the visual inspections and vibrodynamic surveys and the obtained calculation characteristics (2012–2013) allow to characterize the general technical condition of the Center building as unsuitable for normal operation in the nearest future.

5. A systematic assessment of the buildings and structures life resource should take into account the technical condition of all their elements and the results of all types of surveys, including the instrumental and visual inspections, mathematical modeling and their data final synthesis.

6. The experimental and theoretical method of the life resource assessment can be successfully used for the dynamic certification of buildings and structures in Ukraine and is already applied by the SE NDIBK experts in the comprehensive assessment of destroyed and damaged buildings in the cities of Borodianka, Bucha, Vorzel, Gostomel, Irpin, Chernihiv etc., where combat operations have already stopped.

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ДИНАМІЧНА СЕРТИФІКАЦІЯ ТА ОЦІНЮВАННЯ ЖИТТЄВОГО ЦИКЛУ БУДІВЕЛЬ ЗА РЕГУЛЯРНОГО ВИБУХОВОГО ВПЛИВУ / О.М. Трофимчук, Ю.І. Калюх, В.А. Дунін, С.Ю. Кураш

Анотація. Нині в Україні не існує єдиної узаконеної загальноприйнятої методики (на рівні українського будівельного стандарту) динамічної паспортизації будівель і споруд. Запропоновано єдиний підхід у значенні такої методики. Він містить чотири компоненти: візуальний огляд будівель; експериментальні дослідження динамічної реакції будівель або споруд на вибухові дії; математичне моделювання напружено-деформованого стану досліджуваного об'єкта; узагальнення результатів візуального огляду, експериментальних досліджень та числового моделювання з метою їх систематичного узагальнення. Як апробацію наведено погіршення ресурсу залізобетонних конструкцій житлових будинків в умовах постійних масових промислових вибухів потужністю від 500 до 700 тонн в кар'єрі Південного ГЗК (ГЗК) м. Кривий Ріг, Україна. На основі оброблення численних експериментальних даних та результатів математичного моделювання отримано ймовірнісну модель прогнозування погіршення технічного стану залізобетонних конструкцій Центру дитячої та юнацької творчості «Мрія». Розрахунки ризиків руйнування несучих елементів будівлі для її вразливих ділянок дали змогу уточнити термін її експлуатації. Він зменшився приблизно на 30 років порівняно зі стандартом 2012 року.

Ключові слова: ударні хвилі, експеримент, ризик, динамічна паспортизація, життєвий цикл будівель і споруд.